Nuclear Engineering and Design 322 (2017) 485–491

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

On the use of a dedicated ballast pellet for a prompt self-ejection mechanism after a temperature transient in lead-cooled fast reactors

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ARTICLE INFO

Keywords:
Heavy liquid metal fast reactors
Buoyancy
Temperature transient compensation
Generation IV reactors

ABSTRACT

The potential use of changes in buoyancy as a reactivity feedback mechanism during temperature transients in heavy liquid metal fast reactors (HLMFRs) is discussed. It is shown that with the use of ballast pellets (~ 15% volume fraction) introduced in combination with fuel pellets, fuel rods will be endowed with a reliable self-ejection mechanism that is able to compensate temperature transients. Utilizing a simplified model, an estimate of the negative reactivity insertion expected from this mechanism is derived. The use of ballast pellets opens up the possibility of introducing greater amounts of actinides into the core, as well as providing a solution to the classical problem of positive coolant temperature reactivity coefficients in fast reactors.

1. Introduction

One of the unique features of heavy liquid metal fast reactors (HLMFRs) with lead or lead–bismuth eutectic coolant is the very high density of the coolant: the coolant density in HLMFRs is similar to that of the fuel. The potential use of this feature has either been overlooked by nuclear designers or seen as a “nuisance”, and, as a result, preventive measures such as the use of tungsten deadweight (ballast) to overcome buoyancy forces have been proposed (Alessandro, 2014; Di Maio et al., 2014).

The objective of this study was to assess the potential for exploiting changes in buoyancy forces as a control mechanism for fuel rod self-ejection during HLMFR temperature transients, thereby providing a reliable solution to the well-established problem of the positive coolant temperature reactivity coefficient exhibited by sodium fast reactors and also in lead-cooled fast reactors depending on the size of the reactor core. This concept is expected to represent a passive safety feature for the system but it does not represent at all a control device to be used during reactor normal operation.

The effect of buoyancy forces in HLMFRs as a positive aspect in safety analysis during a post-accident heat removal scenario was recently investigated by Arias (2014). It was found that, because of the similar densities of the fuel and the heavy liquid metal (HLM) coolant, an inherent passive safety feedback self-removal mechanism governed by buoyancy is developed, propelling the packed bed away from the wall, and preventing temperatures that could jeopardize the structural integrity of the vessel being reached, as well as reducing the re-criticality potential by limiting the allowable bed depth.

Thus, it is interesting to consider whether buoyancy forces, rather than being regarded as a nuisance during nominal operating conditions, can be harnessed as a mechanism for endowing fuel rods with unique safety properties only available in HLMFRs. In the sections that follow, this possibility will be investigated and discussed. However, the reader should be aware that the results reported in this preliminary analysis of the proposed concept are based on idealizations, of the sort which are inevitable in preliminary theoretical assessments of concepts, and therefore should not be misconstrued as definitive detailed analysis. The final verdict about the feasibility of the proposed concept will only be reached following detailed analysis of the complexities arising from the proposed solutions, the subject of future work. Nonetheless, we feel that this preliminary assessment is appropriate at this time, to encourage (or not) further careful investigation of the idea.

2. Buoyancy forces as a fuel rod ejection mechanism

Fig. 1 illustrates schematically the mechanism we seek to exploit. For the envisaged mechanism to work as intended the density of the coolant needs to become greater than the effective density of the fuel as the temperature increases.

Fig. 2 shows the variation of density as a function of temperature for mixed oxide (MOX) and UO^2 fuels and Pb-Bi eutectic and Pb coolants. This indicates that the relative changes of HLM coolant and fuel densities with temperature are not favorable. However, before deciding on the feasibility of the posited buoyancy mechanism, the fuel densities shown in Fig. 2 need to be corrected to account for the presence of stainless steel, mostly in the form of cladding. Thus, to take into account

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http://dx.doi.org/10.1016/j.nucengdes.2017.07.023
Received 21 May 2017; Received in revised form 16 July 2017; Accepted 18 July 2017
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Nomenclature

B	buoyancy parameter defined by Eq. (20)
C_d	drag coefficient
c_i	heat capacity of material i
F_f	volume fraction of fuel
g	acceleration due to gravity
h	heat transfer coefficient
L	length (of fuel pin or fuel rod)
$\dot{m}_c$	coolant mass flow
M_f	mass of fuel
P	pin power
P^*	pin power at onset of rod ejection
r	radius
R_f	thermal resistance of fuel pin
t	time
T	temperature
T_i	inlet temperature of coolant
V_t	terminal velocity
z	vertical coordinate

Greek symbols

α_i	rate of change of density of material i with temperature
β	fraction of delayed neutrons
γ_c	coolant temperature coefficient of reactivity
κ_i	thermal conductivity of material i
ρ_i	density of material i
ϱ	reactivity

Subscripts

c	coolant
f	fuel
g	gap
s	stainless steel
w	tungsten

the effect of stainless steel on the total density of the fuel, a combined fuel-steel density may be defined as:

$$\bar{\rho}_f = F_f\rho_f + (1-F_f)\rho_s \tag{1}$$

where F_f is the volume fraction of fuel and ρ_f and ρ_s are the densities of the fuel and stainless steel, respectively.

For practical purposes, the densities can be approximated as linear functions of temperature:

$$\rho_i = \rho_{i,0} - \alpha_i T_i \tag{2}$$

where the subscript i denotes the specific material, for example, $i = f$ for fuel, c for coolant, s for stainless steel, and $\rho_{i,0}$ is the density of material i at a temperature of 0 K, α_i is the rate of change of density of material i with temperature, and T_i is the temperature of material i in K. Then, the combined density given by Eq. (1) can be represented as a function of temperatures as:

$$\bar{\rho}_f = \bar{\rho}_{f,0} - \bar{\alpha}_f T_f \tag{3}$$

where

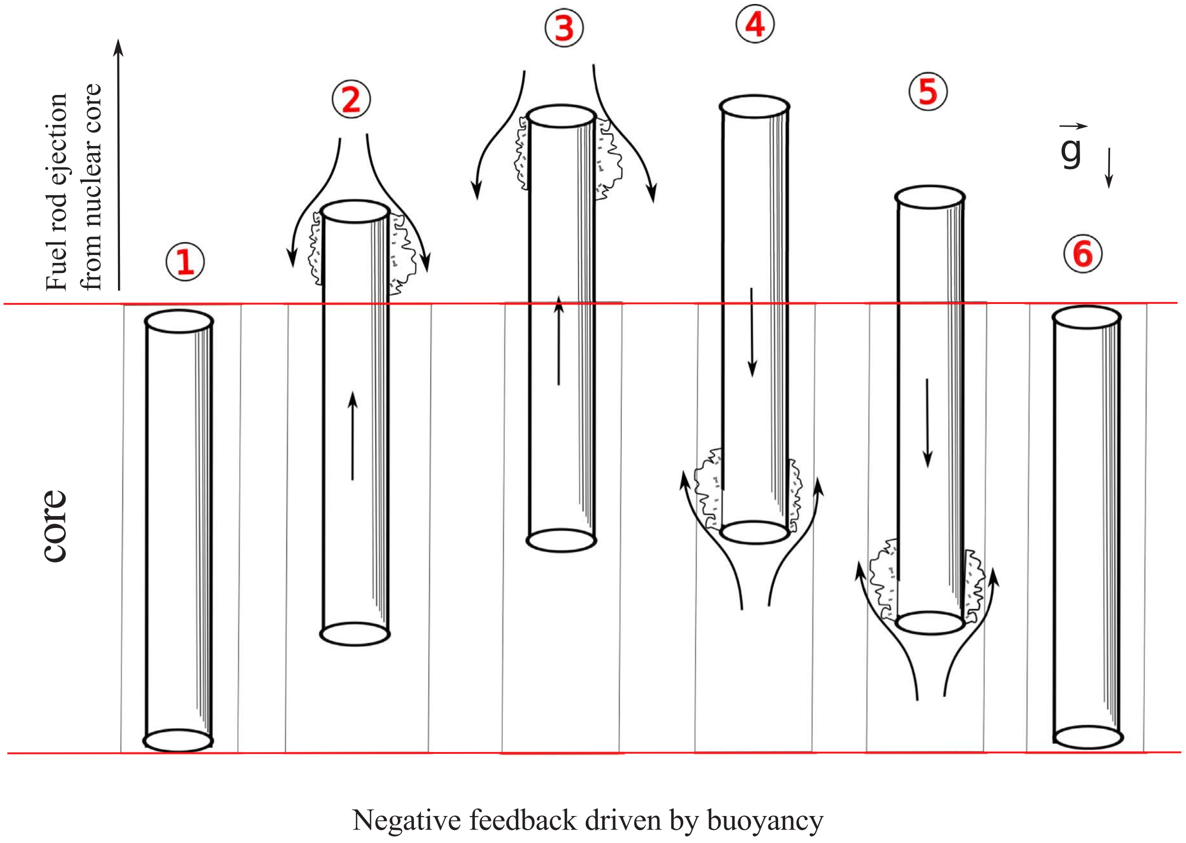

Fig. 1. Fuel rod ejection by buoyancy forces. Sequence: (1) Insertion of reactivity, leading to rising temperatures; (2) Due to relative changes in density with temperature, buoyancy effects act and the fuel rod is propelled upwards; (3) A subcriticality condition is reached, leading to falling temperatures; (4) Relative changes in density lead to loss of buoyancy and the fuel rod falls back down; (5) Fuel rod re-enters the core; (6) End of transient.

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